

Comparison of spectral partitioning techniques for wind wave and swell

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Abstract: The ocean waves are generally mixed with wind wave and swell. In order to separate these two kinds of ocean waves, many wave spectral partitioning techniques have been proposed. In this study, a two-dimensional(2D) and three one-dimensional (1D) wave spectral partitioning techniques (denoted as PM, WH, and JP) are examined based on the model simulations and in-situ observations. It is shown that the 2D technique could provide the most reliable results as a whole. Compared with 2D technique, PM and JP techniques obviously overestimate the wind-wave components, and the same situation happens for WH technique at low wind speed. With the adjustment of the partitioning frequency ratio, the 1D PM technique is modified, in which the result agree well with that of the 2D scheme.

Keywords: wind wave; swell; partition; wave spectrum

1 Introduction

It is well known that the waves in the ocean are commonly mixed with swell and wind wave. The former refers to waves that are generated elsewhere and propagating over long distances, or the local winds slow down or change direction, while the latter is defined as waves in equilibrium with local wind. Because of the different dynamics involved and quite distinct features between them, it is necessary to separate them in the real application. Accurate separation of wind wave and swell is central to a variety of activities, such as air-sea interaction, ocean wave modeling, and coastal engineering.

Many efforts have been devoted to distinguishing between wind wave and swell. Wang(1990)^[1] discussed the criterion for swell, and Guo et al. (1997)^[2] proposed the mixed wave energy composition factor to separate swell from wind wave. These studies mainly focus on determining what kind of ocean waves by using of a criterion, and they did not provide the concrete procedure for the separation of wind wave and swell from the highly mixed sea.

Received on July 10, 2012

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The wave spectrum reflects the inner structure of ocean wave in frequency domain, and spectral partition is suggested to be the best way to isolate wind wave and swell^[3,4]. These methods can be typically categorized into 1D and 2D techniques, which are based on one and two dimensional wave spectrum, respectively. The 2D technique was first proposed by Gerling (1992)^[5]. According to the properties of wind input into ocean waves, the information of wind vector and wave directional spectrum is used to separate wind wave and swell. It is regarded that 2D technique gives more reliable results than that of 1D technique^[6, 7]. However, the 2D technique is very limited in practical application due to the lack of coincident measurement of wind vector and wave directional spectrum. Compared with 2D technique, 1D technique is more convenient to separate wind wave and swell. The basic idea of 1D technique is to set a partition frequency for the wave spectrum, in which the lower frequency and higher frequency part correspond to the swell and wind wave, respectively. Many methods of this kind have been proposed, which is based on the wave frequency spectrum only, or wind speed at the same time. Their reliability can be evaluated by the comparison with 2D technique in the case of natural sea state.

Earle^[8] proposed an 1D technique that simultaneously depends on wave frequency spectrum and wind speed, in which the partition frequency is a function of wind speed (hereinafter referred as PM technique). Some of the 1D techniques separate wind wave and swell based on wave frequency spectrum only. For example, Wang and Hwang(2001)^[9] suggested that the difference of the wave steepness could be used to distinguish wind wave and swell (hereinafter referred as WH technique). According to the overshoot characteristics of wind wave, Portilla et al.^[7] also gave a scheme based on the wave frequency spectrum (hereafter referred as JP technique).

In this study, the 2D technique and three 1D techniques mentioned above were tested through model simulations and in-situ observational data. With the adjustment of ratio coefficient of partition frequency, the PM technique is modified that is more consistent with the results of the 2D technique.

2 Brief description of the partition techniques

2.1 2D partition technique

The 2D partition technique is based on not only the wave directional spectrum, which fully represented the inner structure of ocean wave in frequency and direction domain, but also the wind vector. According to Komen et al. (1984)^[10], the wave component is regarded as pure wind wave when the following relationship is satisfied:

$$\eta \frac{U_{10}}{c} \cos(\theta - \psi) > 1 \quad |\theta - \psi| < \frac{\pi}{2} \quad (1)$$

where U_{10} is the wind speed at 10 m height above the sea surface, c the phase speed, θ the corresponding wave direction, ψ the wind direction, and η is a constant, which is usually chosen as 1.3^[11,12].

2.2 1D partition technique

2.2.1 PM partition technique

Based on the idea that the wind wave and swell correspond to higher frequency and lower frequency part of the wave frequency spectrum, Earle (1984)^[8] suggested that it could be divided by the partition frequency f_s as follows

$$f_s = 0.8 f_{PM} \quad (2)$$

where f_{PM} is the peak frequency of PM wind wave spectrum that corresponds to the fully developed wind wave^[13]. It is only related to wind speed, and can be written as $f_{PM} = 0.13g / U_{10}$, where $g = 9.8 \text{ m/s}^2$ is the gravitational acceleration.

2.2.2 WH partition technique

Based on the wave frequency spectrum observed by buoy, Wang and Hwang (2001)^[9] defined a function of mean wave steepness that can be written as

$$A(f_*) = \frac{8\pi \left[\int_{f_s}^{f_d} f^2 S(f) df \right]}{g \left[\int_{f_s}^{f_d} S(f) df \right]^{1/2}} \quad (3)$$

where $S(f)$ is the wave frequency spectrum, f_d is the upper limit of frequency measured by buoys. They further derived an empirical relationship between f_s and the peak frequency f_m of wave steepness function based on the PM wind wave spectra^[13], which can be expressed as:

$$f_s = A(f_m)^B \quad (4)$$

where $A = 4.112$, $B = 1.746$. Therefore, the WH technique only depends on wave frequency spectrum to calculate the wave steepness function, and the partition frequency can be determined by Eq. (4).

2.2.3 JP partition technique

In the mixed ocean waves, the wave frequency spectrum usually has multi-peaks. The various spectral peaks represent different wave systems. The trough between the two adjacent peaks is regarded as the borderline of wave systems. In this way, the wind wave and swell can be separated from the ocean waves. Portilla et al. [7] defined a coefficient as the ratio λ of measured wave spectrum $S(f_p)$ and PM wave spectrum $S_{PM}(f_p)$ at the spectral peak. It can be written as:

$$\lambda = \frac{S(f_p)}{S_{PM}(f_p)} \quad (5)$$

The wind wave spectrum will exceed the corresponding PM spectrum before it reaches to the fully developed state. This is the so called overshoot phenomenon. The JP partition technique suggested that the wave system was wind wave when $\lambda > 1.0$, otherwise, the wave system was swell. As the WH technique, the JP technique is only related to the wave frequency spectrum, and independent of wind speed.

3 Results and discussion

3.1 Model simulation

One way to test the ability of partition technique is to detect the wind wave and swell from the constructed mixed ocean waves with the specified wave spectra. A Gaussian type swell spectral model [14] and the JONSWAP wind wave spectral model [15] are used to construct the wave spectrum in this study. The JONSWAP frequency spectrum is

$$S_w(f) = \alpha \frac{g^2}{(2\pi)^4} f^{-5} \exp\left\{-1.25\left(\frac{f_0}{f}\right)^4\right\} \gamma^{\exp\left\{\frac{(f-f_0)}{2\sigma^2 f_0}\right\}} \quad (6)$$

where σ is given as:

$$\sigma = \begin{cases} 0.07 & f \leq f_0 \\ 0.09 & f > f_0 \end{cases} \quad (7)$$

and α , f_0 , γ are related to wave age β [16,17].

$$\begin{aligned}\alpha &= 0.0817 (7\pi\beta)^{-6/7} \\ f_0 &= 1.31g / (\pi^2\beta U_{10}) \\ \gamma &= 7.0 (7\pi\beta)^{-3/7}\end{aligned}\quad (8)$$

The 2D wind wave directional spectrum is obtained as the product of wave frequency spectrum and directional spreading function. The directional spreading function $G(\theta)$ is taken as $G(\theta) = 16/5\pi \cos\theta$. The 2D swell spectrum is given as:

$$S_{sw}(f, \theta) = \frac{\langle h^2 \rangle}{2\pi\sigma_f\sigma_\theta} \exp\left\{-0.5\left[\left(\frac{f-f_p}{\sigma_f}\right)^2 + \left(\frac{\theta-\theta_p}{\sigma_\theta}\right)^2\right]\right\} \quad (9)$$

Where $\langle h^2 \rangle$ is the variance of the heights, σ_f and σ_θ are the standard deviations of frequency and wave angle, respectively, f_p is the peak frequency and θ_p is the wave direction corresponding to the spectral peak.

Tab. 1 Relative errors of the spectral technique based on model simulations

Wave state	Parameter	2D	PM	WH	JP	
Swell	(1m,8s,0.005)	0	0	-1	0	
	(1m,8s,0.03)	0	0	-0.83	0	
	(H_s, T_p, σ_f)	(4m,12s,0.005)	0	0	-1	0
		(4m,12s,0.03)	0	0	-0.72	0
		(5m/s,0.5)	0	0	-1	0
		(5m/s,0.9)	-0.06	0	-0.42	0
Wind wave	(10m/s,0.5)	0	0	-0.34	0	
	(U_{10}, β)	(10m/s,0.9)	-0.05	0	-0.18	0
		(15m/s,0.5)	0	0	-0.11	0
		(15m/s,0.9)	-0.05	0	-0.36	0
		Figure 1a (10,0,0.5)	0	0	-0.34	0
		(2.5,14,45,0.005,5)				
Mixed sea	Fig. 1b (10,0,0.9)	-0.05	0	-0.18	0	
	(U_{10}, θ, β)	(2.5,14,45,0.005,5)				
		Figure 2a (6,0,0.9)				
	$(H_s, T_p, \theta_m, \sigma_f, \sigma_\theta)$	(1.2,9,0,0.008,5)	-0.06	0	-0.35	0
		Figure 2b (9,90,0.8)				
		(0.85,7, 0,0.008,5)	-0.03	0.20	-0.19	0.20

In this study, three wave systems, pure wind wave, swell, and mixed wind wave and

swell, are deployed in the numerical simulation. The key parameters and simulation results are listed in Tab. 1. The ability of detecting wave system for the spectral partition techniques is evaluated in terms of the relative error.

The relative errors at various cases for each spectral technique are shown in Tab. 1. In the case of swell, all partition techniques except for WH can detect the swell. The reason for the invalidation of WH technique is the assumption that the wind waves contribute mostly to the total wave steepness. It is obviously not applied in the case of swell. For pure wind wave, both PM and JP techniques perform well, and the 2D technique also detects the wind waves. However, the WH technique can not well distinguish the wind wave when it approaches to the fully developed state ($\beta = 0.9$).

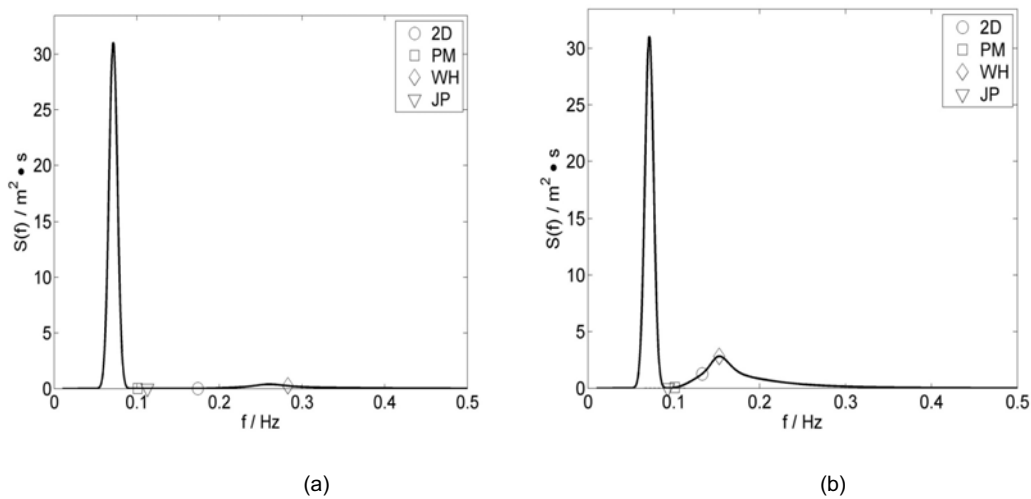


Fig. 1 Coexistence of wind wave and swell radiated from distant storm (a) $\beta=0.5$ (b) $\beta=0.9$

In the case of mixed sea, two kind of swell are considered. The first is that the swell propagates from distant storms, in which the corresponding frequency band is narrow. As shown in Fig. 1, all the partition techniques can separate the wind wave and swell, except for the underestimation of wind waves by WH. The second is that the swell is transformed from the wind wave due to the decrease of wind speed or changing of wind direction. Fig. 2a and 2b show the cases of wind speed decreased from 10 m/s to 6 m/s and wind direction changed from 0° to 90° , respectively. It can be seen that the 2D partition technique can well separate the wind wave and swell in each case, while the WH partition technique has great relative errors. Both PM and JP techniques perform quite well in the former case, and relatively greater errors occur in the latter case. The failure of PM can be ascribed to the neglect of wind direction. The overlap of wind wave and swell can enhance the swell spectrum that leads to the fake overshoot, which will be wrongly detected by the JP

partition technique.

From the above analysis, the 2D partition technique can perform well in each case, and the relative errors are less than 10% in all cases. Compared to the WH partition technique, the PM and JP partition techniques generally give more reliable results. Therefore, the 2D method will be used to validate the three 1D partition techniques with the observational data from buoys.

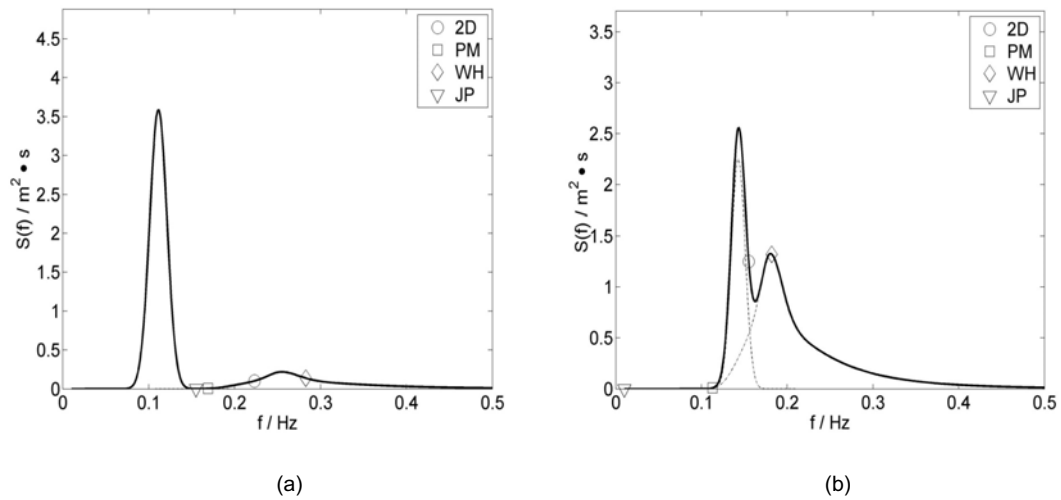


Fig. 2 Coexistence of wind wave and swell generated from wind variation
(a) wind speed decreasing; (b) wind direction changing

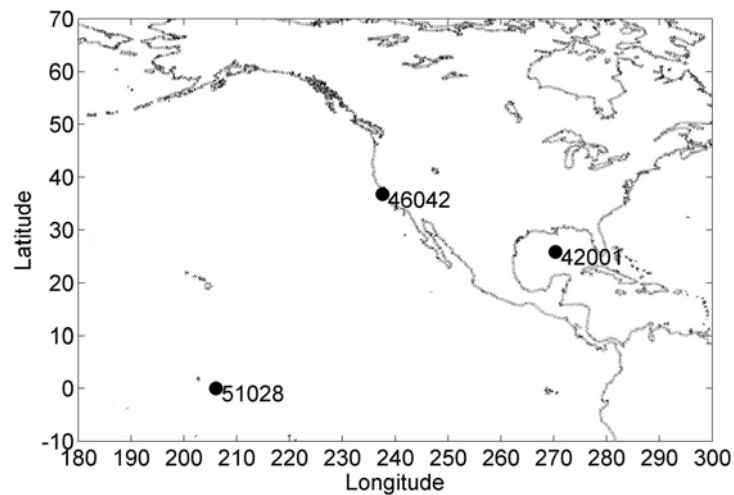


Fig. 3 Locations of NDBC buoys

3.2 Validation with buoy data

The dataset consists of measurements from three buoys operated by the National Data Buoy Center (NDBC) as shown in Fig. 3. One of the buoys 42001 is located in the gulf of Mexico, where Hwang et al. (1998)^[18] suggested that wave energy of swell rarely exceeded 15% of the total spectral energy. The buoy 51028 is in the site of “swell pool” suggested by Chen et al. (2002)^[19], which is dominated by the swell. The observational data from buoy 46042 represent the mixed sea in the natural condition. The observational data measured by the three buoys in the period of 2005 are applied in the following discussion.

Fig. 4 shows the variations of bin-averaged significant wave height (SWH) of wind wave with wind speed with various partition techniques. The fully developed relationship between SWH and wind speed^[20] is also plotted for reference in Fig. 4. It can be seen that PM technique systematically overestimates the SWH compared with the fully developed relationship in the wind speed range of 5 m/s - 10 m/s. The results of WH technique also significantly overestimate the SWH when the wind speed is less than 6m/s, and are consistent with those of the 2D technique at higher wind speed. The results of JP technique are generally consistent with those of the 2D technique, although they slightly exceed the fully developed relationship at the low wind speeds.

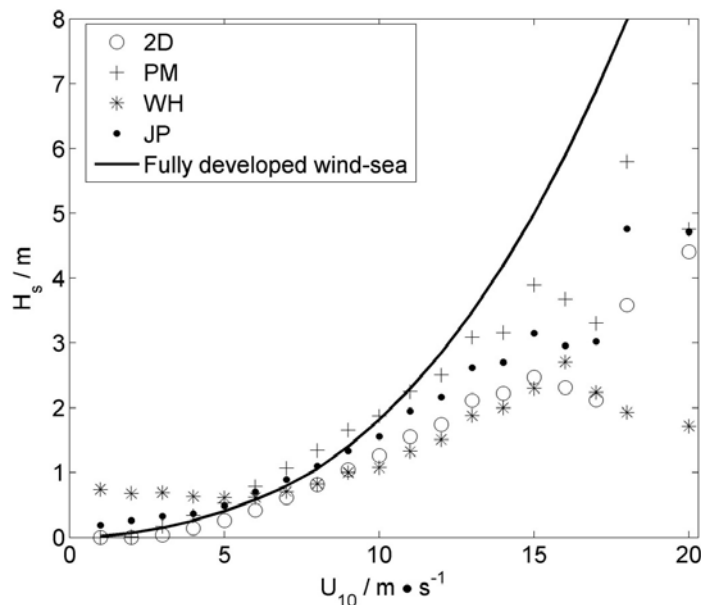
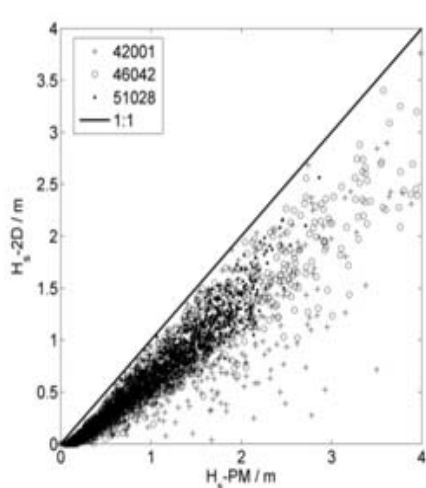


Fig. 4 Variations of the SWH of wind wave derived from different spectral techniques with wind speed

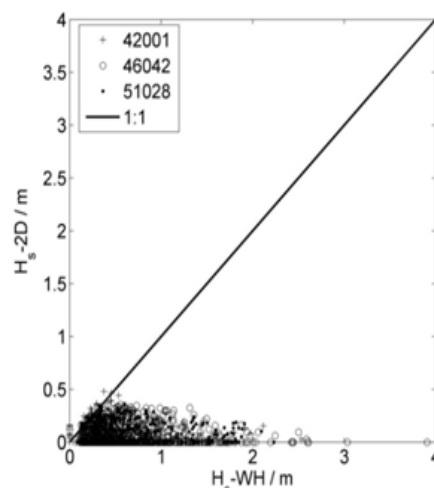
Direct comparison between the 1D techniques and 2D technique is shown in Fig. 5. The systematic overestimation of PM technique is quite obvious as shown in Fig. 5a, which has been previously suggested by Portilla et al.(2009)^[7]. WH technique significantly overestimates the wind wave at the wind speed of 0 m/s - 6 m/s (Fig. 5b), this is because the sea is frequently dominated by swell at low wind speeds ^[19]. Gilhousen and Hervey(2001)^[21] also pointed out the same problem, and they suggested that additional wind information should be used to improve the performance. The results given by WH technique at higher wind speeds are generally consistent with those of 2D technique (Fig. 5c), although the large scatter is observed. In general, the results of JP technique are greater than those of 2D technique, especially at high wind speeds. Quantitative comparisons of 1D techniques with 2D technique are given in Tab. 2 in terms of bias and root mean square error (RMSE). It can be seen that WH technique has the lowest bias, while its RMSE is the largest. On the contrary, the PM technique has the largest bias, and its RMSE is the lowest.

Tab. 2 Errors of each 1D spectral technique from field tests

	42001		46042		51028		Total	
	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
PM	0.35	0.53	0.35	0.46	0.37	0.41	0.37	0.50
WH	0.29	0.61	0.23	0.68	0.07	0.49	0.22	0.60
JP	0.31	0.59	0.28	0.54	0.16	0.30	0.28	0.52
Improved PM	0.05	0.22	-0.01	0.11	-0.03	0.06	0.05	0.18



(a)



(b)

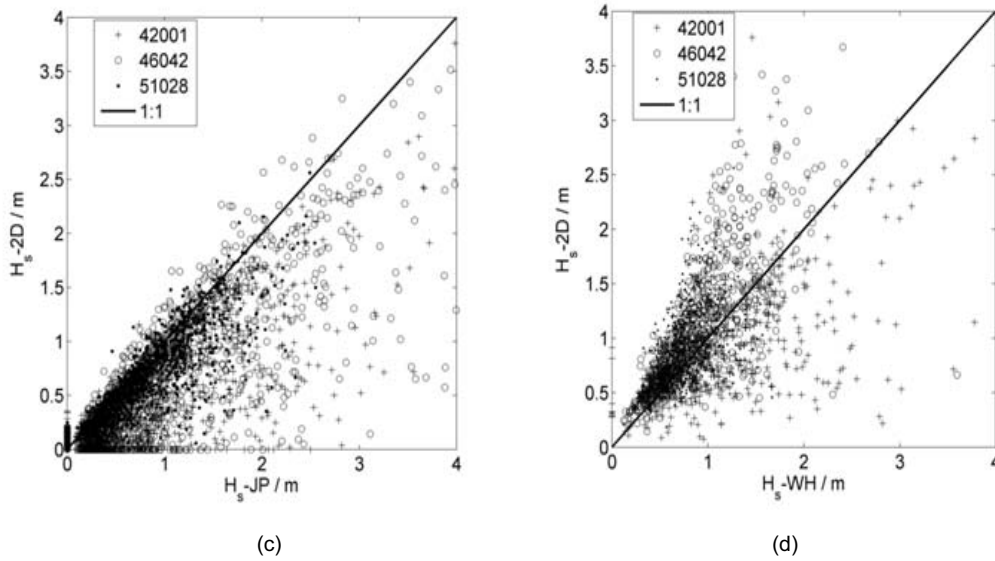


Fig. 5 Comparison of the SWH of wind wave from 2D technique with that given by (a) PM, (b) WH at wind speed up to 6 m/s, (c) WH at wind speed higher than 6 m/s, (d) JP

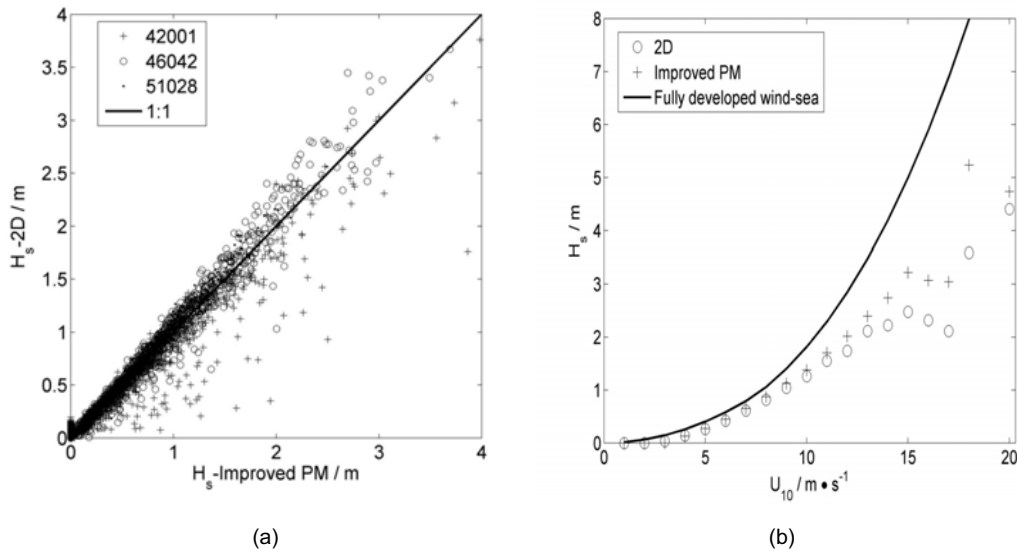


Fig. 6 Comparison of the 2D technique with the improved PM technique in terms of the SWH of wind wave (a) 1:1 comparison (b) in terms of variation with wind speed

The overestimation of wind wave by PM technique can be easily improved by the adjustment of the partition frequency f_s . It is found that the PM technique gives the best agreements with 2D technique when $f_s = 1.2f_{PM}$ replaces the Eq. (2) (Figure 6 and Table 2). On the other hand, almost the same relationship ($f_s = 1.22f_{PM}$) can be derived by assuming that the corresponding phase velocity of f_s equals U_{10} , i.e. $g/2\pi f_s = U_{10}$). In

addition, it is shown by the numerical model that waves for $f > 1.25f_{PM}$ decay quickly[22], which indicates that it is physically reasonable by using $f_s = 1.2f_{PM}$ to separate the wind wave and swell.

4 Summary

In this study, the performance of the 2D wave spectral partitioning technique and three 1D wave spectral partitioning techniques are examined through the model simulations and the in-situ observations. In general, the 2D technique can provide the most reliable results, and it is used as a reference to examine the 1D techniques. It is found that PM technique obviously overestimates the wind wave components, and the same situation happens to WH technique at lower wind speeds, while it is consistent with 2D technique at higher wind speed. The results of JP technique are generally greater than those of 2D technique. With the adjustment of partition frequency, the PM technique is improved, in which, it performs best in terms of bias and RMSE.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (No. 41076007) and the National Basic Research Program of China (No. 2009CB421200).

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风浪和涌浪分离方法的比较

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摘要: 海浪通常以风浪和涌浪混合的形式存在, 如何进行分离风浪和涌浪一直是海浪理论研究和海洋工程应用中的重要问题。本文利用模型试验和实测资料, 对目前提出的一种二维谱风涌浪分离方法(2D法)和三种一维谱风涌浪分离方法(PM法、WH法、JP法)进行了检验, 分析发现: 2D法给出的结果整体而言最为可靠, 与2D法相比, PM法明显高估了风浪成分, WH法低风速时高估了风浪, 高风速时跟2D法比较接近, 而JP法在整体上高估了风浪成分。通过调整分割频率的比例系数, 改进了PM法, 改进后的PM法给出的分离结果与2D法最为一致。

关键词: 风浪; 涌浪; 分离; 海浪频谱